

# **Design Issues for Commercial Scale Ground-Source Heat Pump Systems**

*Gary Phetteplace, Ph.D., P.E.*  
CECRL-AR  
603-646-4248

*Steve Kavanaugh, Ph.D.*  
University of Alabama  
205-348-1649

## **INTRODUCTION**

Ground-source heat pump (GSHP) technology has gained widespread acceptance in the private sector in the last five years. A number of military bases have installed systems and due to their success and the general growth of the concept in the private sector, increasing emphasis is being placed on this technology by DoD. For example, GSHP technology has been specifically named in the Army's Implementation Plan for Sustainable Design. However, despite the recent increase in activity in this area, the general level of awareness and expertise in the CoE and the HVAC design community at large is inadequate to ensure successful, cost effective, designs. This paper will provide a very brief introduction to some of the key design issues. Those who are interested in gaining additional insight into the design of these systems should attend a training course on the topic. Several private sources of training exist and efforts are underway to offer additional workshops similar to those sponsored by the US Army CoE Center for Public Works in the last two years. The authors may be contacted for details on available training.

## **BASIC SYSTEM TYPES**

Ground source heat pump systems use the ground as a heat source in the heating mode and heat sink in the cooling mode. The ground is an attractive heat source or sink when compared to outdoor air because of its relatively stable temperature. Figure 1 shows some soil temperatures recorded from heat pump demonstration projects conducted by CRREL at Ft. Polk (ref. 1). It's clear from Figure 1 that the soil temperature does not vary significantly over the annual cycle below a depth of about 2 meters. (6.5 feet). While outdoor air temperatures may range from wintertime lows of 0°C (32°F) (Ref. 2) or lower to

FIGURE 1: FT. POLK SOIL TEMPERATURES

summertime highs around 33°C (95°F) (Ref. 2), the soil temperature at depths greater than two meters never falls below about 18°C (64°F) or rises about approximately 25°C (77°F), averaging around 20°C (68°F).

A number of different methods have evolved for thermally connecting or "coupling" the heat pump systems with the ground. Here we will only describe the most common types of ground-source systems. The emphasis of the paper will be on vertical systems because they are the most common in commercial scale design. However, the other types are occasionally used in commercial scale design and the designer should be aware of these alternatives. In addition to the types of ground-coupled systems discussed here systems that use both surface water and ground water have been successfully used. In fact, for commercial scale applications if ground water is available in sufficient quantities, it should be considered as the first alternative as it will often turn out to be the least costly. Design information for ground water and surface water systems may be found in several design manuals(Refs. 3 and 4).

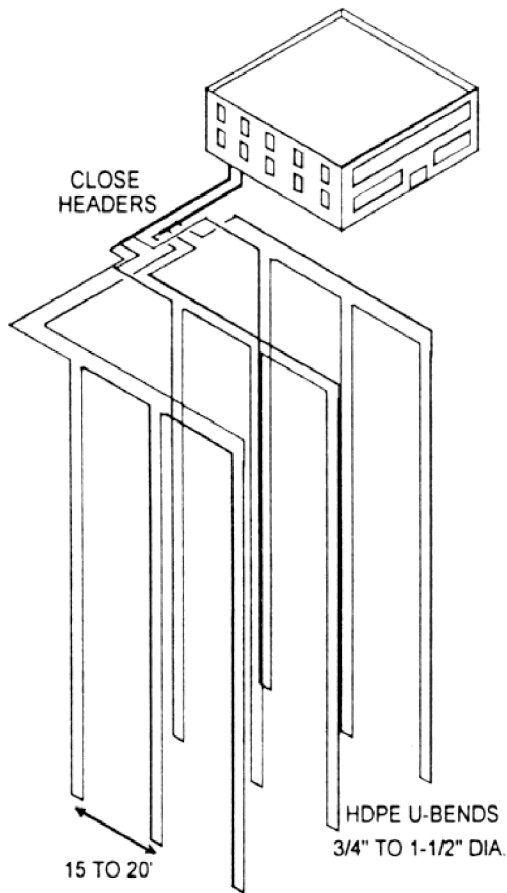


FIGURE 2: TYPICAL VERTICAL GROUND COUPLING SYSTEM

#### VERTICAL GROUND-COUPLED

As noted earlier, vertical ground-coupling is the most common type of system in commercial scale systems. Figure 2 shows the basic arrangement of a vertical ground coupled system. Vertical u-tube plastic piping, to be described in more detail later, is placed in bore holes and is manifolded in shallow trenches at the surface. The specifics of borehole design, completion, piping materials, and methods are discussed later. Vertical ground coupling has several advantages: low land area requirements, stable deep soil temperatures with greater potential for heat exchange with ground water, and adaptability to most sites. Among vertical ground-coupling's disadvantages are potentially higher cost, problems in some geological formations, and the need for an experienced driller/installer.

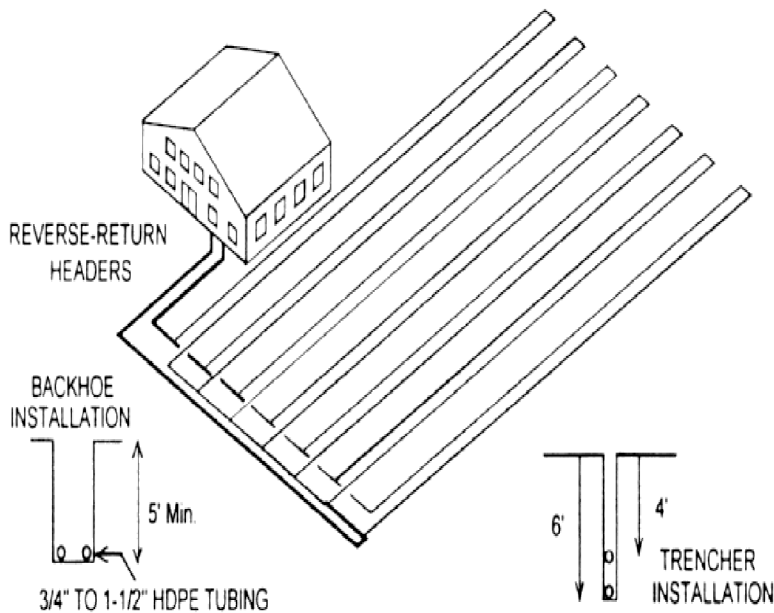


FIGURE 3: TYPICAL HORIZONTAL GROUND-COUPLED SYSTEM.

#### HORIZONTAL GROUND-COUPLED

Horizontal ground-coupling uses plastic piping placed in horizontal trenches to exchange heat with the ground, see Figure 3. Piping may be placed in the trenches either singly or in multiple pipe arrangements. The primary advantage of horizontal systems is lower cost. This results primarily from fewer requirements for special skills and equipment combined with less uncertainty in subsurface site conditions. The disadvantages of horizontal ground-coupling are its high land area requirements, its limited potential for heat exchange with the groundwater, and the wider temperature swings of the soil at the typical burial depths.

A variant of the horizontal systems is the horizontal "slinky" system shown in Figure 4. These systems have the same advantages as conventional horizontal systems but require less land area and are adaptable to a wider range of construction equipment.

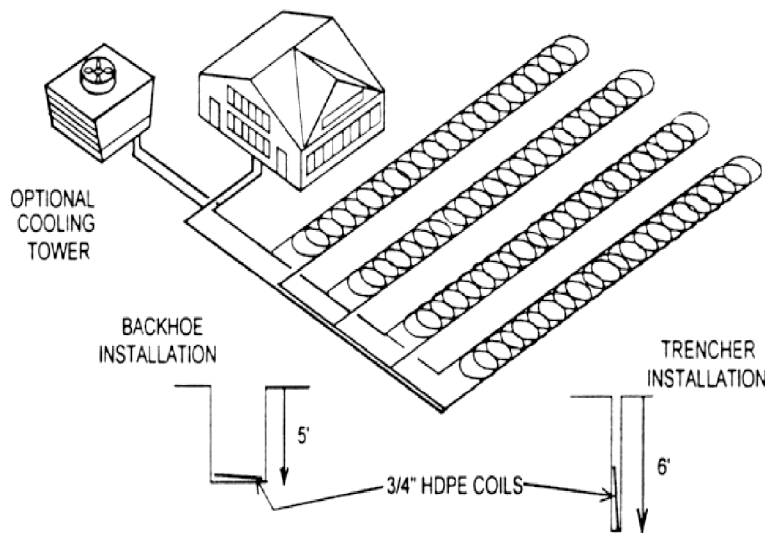


FIGURE 4: TYPICAL SLINKY GROUND-COUPLED

#### GROUND SOURCE VS CONVENTIONAL EQUIPMENT

GSHPs have a number of advantages compared to conventional equipment such as variable air volume (VAV) systems. With individual heat pumps serving each zone, control and comfort are superior to many other types of systems using large central equipment. This ideal zone control coupled with the unitary design of the equipment results in simple but highly reliable systems that can be maintained without the need for special skills. Operating costs for these systems tend to be lower than for conventional equipment, especially when all the parasitic losses of large central systems are considered. The heat pumps themselves, like their sister technology the household refrigerator, tend to be very reliable with low maintenance and long lifetimes. GSHP systems require no on-site fuel storage and are considered a green technology with no on-site, unregulated, emissions. Finally, because the equipment is distributed around the building, mechanical room space requirements are greatly reduced or in some cases eliminated altogether.

The primary disadvantage of GSHP is that they tend to have higher initial costs than some conventional systems. In commercial applications, however, they are able to compete favorably on a first cost basis against some of the more costly conventional systems, i.e. four-pipe systems. In many other applications any additional initial investment will be quickly returned in reduced operating and maintenance costs.

In some regions the lack of GSHP infrastructure can be an

additional disadvantage of GSHP systems. In areas where GSHP's have not seen much development to date it may be difficult to locate experienced designers and installers. However, in many cases it is possible to procure these services from outside the area at competitive prices.

## **BUILDING LOADS AND HEAT PUMP SELECTION**

The design of a GSHP system begins like any other project with the calculation of building loads. However, unlike equipment that rejects heat to air or extracts heat from air, GSHP equipment can have a substantial impact on its heat source/sink, the ground. Thus, rather than being based solely on the maximum amount of energy rejected to/extracted from the ground, the amount of heat rejection/heat extraction must be known along with its history. Thus, when calculating the building loads you should keep in mind the level of detail that will be required by the software to be used in designing the ground loop, as discussed in the next section. Of course, equipment will still be sized based on the maximum zone loads.

A number of different types of water-source heat pumps are available for use in GSHP systems. Both upflow and downflow units are available as well as horizontal and console units. Water-to-water units are also available for radiant floor heating applications, hot water heating, or ventilation air preconditioning. Typical commercial scale application use units mounted in the ceiling space or small utility closets. These units are quiet enough such that noise is not generally a problem.

As noted above, one of the principal advantages of GSHP, or for that matter the more conventional water loop heat pump system using a boiler and cooling tower, is the flexibility of zoning. In general it is best to treat each zone with it's own individual heat pump. In addition, there is little, if any, advantage to using a larger unit to serve several areas even if they are reasonably served as a single zone. There are two reasons why the "bigger is better" mentality may not be best with GSHP systems:

In general the smaller heat pump units themselves have higher efficiencies than larger units.

The cost advantage of a single larger unit over multiple smaller units is modest and will be easily offset by ducting costs.

In concert with the decision on how to serve the zones with heat pumps, a decision needs to be made regarding the best way to

configure the ground coupling loops that will serve the heat pumps. The principal options are:

Connect all heat pumps to a common circulating loop and a common set of ground-coupling wells. This works best for compact floor plans and allows the maximum benefit to be derived from diversity of the zone loads.

Provide a separate ground-coupling loop field for each heat pump unit. This works well where the floor plan is spread out, like school buildings, and in retrofit situations where it would be difficult to run piping for the central circulating loop. It thwarts any attempt to take advantage of diversity, but provides redundancy such that any system failures will only affect single zones.

Some combination of the two solutions above. This solution offers exceptional flexibility for buildings that don't fall clearly into one of the categories above.

Consult GSHP design manuals (Refs. 3,4) for more detailed discussion and examples of possible arrangements of heat pump units and zones, methods of pumping for the circulating loop, and control of the pumps.

Water source heat pumps are rated in accordance with three Air Conditioning and Refrigeration Institute (ARI) Standards, they are:

ARI 320 (Ref. 5). This standard is intended for normal water loop heat pump installations that use a boiler and cooling tower to keep entering water temperature (EWT) to the heat pumps within a narrow range, with the rating given being for EWT's of 21.1°C (70°F) in the heating mode and 29.4 °C (85°F) in the cooling mode. This standard contains no allowance for pumping energy consumption.

ARI 325 (Ref. 6). This standard is intended for open loop systems that use ground water directly as the heat source and sink. For this standard the heat pumps are rated at two EWT's in both the heating and cooling mode. For heating and cooling both the two rating conditions on EWT are 10°C (50°F) and 21.1°C (70°F). This standard contains a substantial penalty for pump power that is reflective of residential groundwater systems, but it's not appropriate for ground-coupled heat pump (GCHP) systems.

ARI 330 (Ref. 7). This standard is intended for residential GCHP systems. The rating EWT's are 0°C (32°F) in heating and

25°C (77°F) in cooling. These rating temperatures, for both heating and cooling, are in general too low for what would be experienced in commercial buildings in all but the most heating dominated climates. For this reason heating COP's will generally be greater than those given by ARI 330 and conversely cooling capacities and EER's will be less at peak conditions. A reasonable penalty for pumping energy consumption has been included.

In most cases for GCHP systems the most appropriate rating standard will be ARI 330-93 (Ref. 7). Some suggested requirements for the heat pump units are:

Extended temperature range capability allowing operation from -4°C (25°F) to 40°C (104°F).

Minimum EER of 13.5 rated in accordance with ARI 330-93 (Ref. 7). Do not allow multi-speed or variable speed units to be rated at any condition other than high speed on compressor and fan. Rating under lower compressor speeds with high fan speed results in impressive EER, but little or no latent heat removal will be possible under this condition.

The head loss in the water coil of the heat pump should not exceed 45 kPa (15 feet of water) when the flow rate is at 0.19 L/s (3 gpm) per nominal ton of cooling capacity.

Avoid the use of heat pumps that require proprietary thermostats and controls. These can be difficult to maintain without special skills and equipment and simply are not necessary for most systems.

Aside from the energy efficiency motive for specifying high efficiency equipment the designer should be aware of two other major advantages of high efficiency heat pumps:

High efficiency equipment will discard less heat to the ground loop in the cooling mode and will require smaller ground loops helping to avoid costs on this expensive part of the project.

High efficiency units will perform much better at conditions other than the design point. Thus, if for example in the cooling mode the EWT ends up being higher than planned, high efficiency units will lose much less capacity and sacrifice much less efficiency than will lower efficiency units.

## **DESIGN OF VERTICAL GROUND-COUPLING HEAT EXCHANGERS**

Because of the diversity in loads in multizone building, the design of the ground coupling heat exchanger must be based on peak block load rather than the installed capacity. This is of paramount importance as ground coupling is usually a major portion of the total GCHP system cost and oversizing will render a project economically unattractive.

While in the residential sector many systems have been designed using rules-of-thumb and local experience, for commercial scale systems such practices are ill advised. For all but the most northern climates, commercial scale buildings will have significantly more heat rejection than extraction. This imbalance in heat rejection/extraction can cause heat buildup in the ground to the point where heat pump performance will be adversely affected and hence system efficiency and possibly occupant comfort will suffer. Proper design for commercial scale systems almost always requires the use of computer aided design (CAD) software. CAD software for commercial scale GCHP design should consider the interaction of adjacent loops and predict the potential for long term heat buildup in the soil. Some sources of PC based CAD software packages that address this need are given below:

GchpCalc Version 3.1, Energy Information Services, 1-205-799-4591, \$300. This program includes built in tables for heat pump equipment from most manufacturers. Input is in the form of daily heat loss and gains at design conditions, approximate annual full load hours, and desired operating temperatures. Primary output from the program is the ground loop length required. This program will also calculate the optimal size for a supplemental fluid cooler for hybrid systems as discussed later. (This program has been used in the two design courses offered to DoD to date)

- GLHEPRO, International Ground Source Heat Pump Association (IGSHPA), 800-626-4747, "<http://www.mae.okstate.edu/Faculty/spitler/glhewin/glhepro.html>", \$500. Input required is monthly heating/cooling loads on heat pumps and monthly peak loads either entered directly by user or read from BLAST or Trane System Analyzer and Trane Trace output files. The current configuration of the program has some constraints on selection of borehole spacing, depth, and overall layout. These constraints will be removed on a future version now being prepared.

GS2000 Version 2.0, Caneta Research Inc., 905-542-2890, email: [caneta@compuserve.com](mailto:caneta@compuserve.com), \$350. Heating/cooling loads are input as monthly totals on heat pumps or alternately monthly loads on the ground loop may be input. Equipment performance is input at ARI rating conditions discussed

above. For operating conditions other than the rating conditions the equipment performance is adjusted based on generic heat pump performance relationships.

Each of these CAD programs will require input about the soil thermal properties, borehole resistance, type of piping and borehole arrangement, fluid to be used, and other design parameters. Many of the required inputs will be available from tables of default values. The designer should be careful to ensure that the values chosen are representative of the actual conditions to be encountered in order to ensure efficient and cost effective designs. Test borings to determine the type soil formations and aquifer locations will substantially improve design accuracy and may help reduce costs. Even with the information from test borings some uncertainty will remain with respect to the soil thermal properties. CAD programs make it possible to easily vary design parameters within the range of anticipated values and determine the sensitivity of the design to a particular parameter. In some instances, particularly very large projects, it may be advisable to obtain specific information on ground loop performance by doing thermal testing of a sample borehole. There are several commercially available sources for such testing.

In heating dominated climates a mixture of antifreeze and water will need to be used in the ground coupling loops if loop temperatures are expected to fall below about 5°C (41°F). A recent study (Ref. 9) establishes the important considerations for antifreeze solutions for GCHP systems and provides guidance on selection.

The regulatory requirements for vertical boreholes used for ground coupling heat exchangers varies widely by state. Current state and federal regulations as well as related building codes are summarized at "<http://www.uidaho.edu/ghpc>" as are contacts within these regulatory bodies. One note of caution to the designer: some regulations, installation manuals, and/or local practices call for partial or full grouting of the borehole. The thermal conductivity of materials normally used for grouting are very low when compared to the thermal conductivity of most native soil formations. Thus, grouting will tend to act as insulation and hinder heat transfer to the ground. Some recent experimental work (Ref.8) has confirmed the negative impact of grout on bore hole heat transfer. Under heat rejection loading average water temperature was nearly 6°C (11°F) higher for a 16.5 cm (6.5 in.) diameter borehole backfilled with standard bentonite grout when compared to a 12.1 cm (4.75 in.) diameter borehole backfilled with thermally enhanced bentonite grout. Using fine sand as backfill in a 16.5 cm (6.5 in.) diameter borehole lowered the average water temperature over 8°C (14°F) when compared to the

same diameter bore backfilled with standard bentonite grout. For a typical system (Ref.8) with a 16.5 cm (6.5 in.) diameter borehole the use of standard bentonite grout would increase the bore length required by 49% over fine sand backfill in the same borehole. By using thermally enhanced grout in a smaller 12.1 cm (4.75 in.) borehole the bore length is only increased by only 10% over fine sand backfill in the larger 16.5 cm (6.5 in.) diameter borehole. Thus the results of this study (Ref.8) suggests three steps that may be taken to reduce the impact of grout on system performance:

Reduce the amount of grout used to the bare minimum. Sand or cuttings may be used where allowed but care must be used to ensure that the entire interstitial space between the piping and the borehole diameter is filled.

Use thermally enhanced grout wherever possible. For information on thermally enhanced grout consult Ref. 4 and Ref. 8.

Reduce the borehole diameter as much as possible to mitigate the effects of whatever grout or backfill is used.

## **PIPING AND PUMPS FOR GCHP SYSTEMS**

Failures in early GCHP systems have led to standard practice and materials for the buried piping used in these systems that will result in long reliable lifetimes. The only piping material that is now used for the buried portion of the systems is high density polyethylene (HDPE) of very specific grades. All joints are thermally fused, either butt or socket type. Specifications for the piping material and joining process may be found in Ref. 3 and Ref. 4. Installers of these systems are certified by International Ground Source Heat Pump Association (IGSHPA), or by equivalent programs provided by some equipment suppliers, after being trained and demonstrating competency with the materials and methods. For piping within the building any of the normally acceptable materials may be used that are in accordance with local codes.

Many possible header arrangements exist for connecting the multiple ground-coupling wells that exist in a typical commercial scale project. The conflicting objectives that must be considered in designing the headers and sizing the piping are the desire to reduce pumping power consumption and the need to avoid laminar flow which inhibits fluid side heat transfer. Available design manuals (Refs.3, 4) contain recommendations for layout and sizing of multiple ground loop systems. An additional consideration for ground-loop piping is the placement of purge

valves at strategic locations in the supply and return headers.

Pumping energy consumption in GCHP can be excessive if proper care is not taken in the design. Pumping energy consumption will be acceptable if the following guidelines are observed:

Size piping and headers properly based on the recommendations of accepted design guides (Refs. 3, 4).

- Avoid the use of antifreeze unless necessary and if so keep concentrations to a minimum.
- Use variable speed pumping and two-way valves at the heat pumps for all centrally pumped systems.
- Use pumps with high efficiency motors and design them to operate near their point of maximum efficiency.

Select heat pumps and control valves with low pressure drops.

Do not pump more fluid to the heat pumps than necessary. High efficiency units will operate with little performance degradation at lower flow rates.

One design manual (Ref. 4) suggests the following benchmarks for pumping energy consumption:

| Pump Input Power/Cooling Capacity<br>(W/Ton) |       | Relative Ranking |
|--|-------|------------------|
| #50  | #5    | Excellent        |
| 50-75  | 5-7½  | Good             |
| 75-100                                       | 7½-10 | Mediocre         |
| 100-150                                      | 10-15 | Poor             |
| >150   | >15   | Bad              |

## DEALING WITH VENTILATION AIR REQUIREMENTS

Emphasis on improved indoor air quality requires much more careful treatment of ventilation air requirements than in the past. Heating and cooling this ventilation air can become a major load for the HVAC system. GCHP's are able to deal with these ventilation loads as long as they are addressed at the outset. The various types of GCHP system arrangements lend themselves to differing solutions. For example, for a classroom or hotel type application in a moderate climate it may be acceptable to use console type heat pump units and provide ventilation air through the wall directly to the unit. For larger systems that will have ducted ventilation air to the

units, in heating dominated climates a sensible heat recovery unit may provide the best solution to preconditioning the ventilation air. Another solution for ducted systems in heating dominated climates would be to use a coil for preconditioning the ventilation air. The water/antifreeze solution circulated to the coil could be either heated by fossil fuel, electricity, or a water-to-water heat pump.

Providing ventilation air can be very problematic in humid air conditioning climates as well because of all the excess humidity that it brings into the conditioned space. The water-to-air heat pumps used in GCHP systems have a real advantage here as they have very high latent capacity. For this reason it may not be necessary to consider total heat recovery units in GCHP systems. The use of coils to precondition air is also an option in the air-conditioning mode as well. The chilled water for the coils can be provided by a water-to-water heat pump. When this is done it is possible to downsize the individual zone heat pumps. Under part load conditions this arrangement will provide better humidity control by dehumidifying the incoming air stream effectively. Several detailed examples of methods for handling ventilation air in GCHP systems are contained in Ref. 4.

#### **HYBRID SYSTEMS AND OTHER COST CONTROL MEASURES**

As noted above, even in northern climates HVAC requirements of commercial scale buildings are often dominated by air conditioning. For ground coupled systems that use the ground as a heat source/sink large imbalances between heat rejection and addition can present a problem. The CAD programs for ground loop design discussed above allow the designer to assure himself that heat buildup in the ground will not cause problems over the system's lifetime. However, where large imbalances exist adding a cooling tower is an option that will help reduce the imbalance and also reduce the amount of ground loop required. Closed circuit fluid coolers are often used for this purpose with this type of system often referred to as a "Hybrid GCHP". While the previous mentioned manuals (Ref. 3 and Ref. 4) provide some discussion of supplemental heat rejection with cooling towers, the best source of information on design methods is a recent report (Ref. 10).

A hybrid design is one of many cost control measures available to designers of GCHP systems. GCHP are inherently simple systems and controlling costs in GCHP system design is easily done as long as the designer does not try to use methods and equipment more appropriate to conventional systems design. An excellent example of this is found in system control. Because the GCHP systems achieves zone control via individual heat pump units

serving each zone, elaborate controls (i.e. DDC) are neither necessary or desirable. The designer new to GCHP systems would be wise to consult a separate chapter in one of the current design handbooks (Ref. 4) devoted to cost control measures in GCHP systems.

## **SOURCES OF INFORMATION**

Aside from the references cited here there are a number of other sources of information available to the designer. In some cases it may be possible to obtain design assistance through programs sponsored by one of the major proponent organizations for this technology, the Geothermal Heat Pump Consortium (GHPC) located in Washington, DC. They may be contacted at 1-888-ALL-4-GEO or visit their website at "<http://www.ghpc.org>". The GHPC is a public/private venture funded by DoE, electric utilities, and manufacturers of heat pumps and allied equipment used in the industry. While their primary focus is marketing of the technology, to that end they do provide various materials and services useful to the designer.

Another source of information is the International Ground Source Heat Pump Association (IGSHPA) located at Oklahoma State University. They can be reached at 1-800-626-4747 or via their website at "<http://www.IGSHPA.okstate.edu>". IGSHPA provides various training opportunities, primarily to systems installers, as well as design software, and a number of publications.

The Geo-Heat Center funded by DoE and located at the Oregon Institute of Technology also provides information and assistance. They can be reached at 541-885-1750 or via their web site at "<http://www.oit.edu/~geoheat>". The University of Alabama and the Geo-Heat Center have recently initiated the publication of a quarterly newsletter (*Outside the Loop*) with a focus on information of interest to engineers and contractors.

## **REFERENCES**

1. Phetteplace, G., H. Ueda, and D. Carbee (April 1992). Performance of Ground-Coupled Heat Pumps in Military Family Housing Units, proceedings of the 1992 ASME International Solar Energy Conference, Maui, Hawaii, 4-8 April 1992, pages 377-383.
2. Department of the Army (July 1978). Engineering Weather Data, Technical Manual TM 5-785.
3. American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) (1995). Commercial/Institutional

Ground-Source Heat Pump Engineering Manual, ASHRAE, Atlanta, GA.

4. American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) (1997). Ground Source Heat Pumps - Design of Geothermal Systems for Commercial and Institutional Buildings, ASHRAE, Atlanta, GA.

5. Air Conditioning and Refrigeration Institute (ARI), "Water Source Heat Pump Equipment", Standard ARI 320-93, ARI, Arlington, VA.

6. Air Conditioning and Refrigeration Institute (ARI), "Ground Water Source Heat Pump Equipment", Standard ARI 325-93, ARI, Arlington, VA.

7. Air Conditioning and Refrigeration Institute (ARI), "Ground Source Closed-Loop Heat Pump Equipment", Standard ARI 330-93, ARI, Arlington, VA.

8. Spilker, Elliott H. (January 1998). "Ground-Coupled Heat Pump Loop Design Using Thermal Conductivity Testing and the Effect of Different Backfill Materials on Vertical Bore Length", Proceeding of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), January 1998 meeting, San Francisco CA, paper SF98-1-3.

9. Heinonen, E.W., Tapscott, R.E., Wildin, M.W., and Beall, A.N. (February 1997). "Assessment of Antifreeze Solutions for Ground-Source Heat Pump Systems", Report 908RP, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA.

10. Kavanaugh, S.P. (1997). "Analysis and Development of a Design Method for Hybrid Geothermal Heat Pumps", Final report, Geothermal Heat Pump Consortium, Washington, DC  
"http://www.ghpc.org"

**AUTHOR'S ADDRESSES:** Gary Phetteplace  
US Army Cold Regions  
Research and Engineering Laboratory  
72 Lyme Road  
Hanover, NH 03755-1290  
Phone: 603-646-4248  
Fax: 603-646-4380/4640  
Email: gephnet@crrel.usace.army.mil  
  
Prof. Steve Kavanaugh  
University of Alabama  
Department of Mechanical Engineering

PO Box 870276  
Tuscaloosa, Al 35487-0276  
Phone: 205-348-1649  
Fax: 205-348-6419  
email: [skavanaugh@coe.eng.ua.edu](mailto:skavanaugh@coe.eng.ua.edu)